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DAMBREAK FLOOD IMPACT ON MOUNTAIN STREAM BEDLOAD TRANSPORT AFTER 13 YEARS

JAMES C. BATHURST* AND MUHAMMAD ASHIQ†

Water Resource Systems Research Laboratory, Department of Civil Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU, UK

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ABSTRACT

Studies of the bedload transport regime of the Roaring River, Colorado, in 1984–88, following a dambreak flood in 1982, showed that bedload transport rates were an order of magnitude higher than under pre-flood conditions. A gorge eroded by the flood in glacial moraine acted as a major sediment supply source. Measurements in early June 1995 showed a continued potential for high sediment supply from the gorge and a bedload transport regime similar to that of 1984–88. A major snowmelt flood in mid-June flushed sediment supplies from the gorge and measurements in July showed a corresponding reduction in bedload transport. However, high sediment supply will continue until the gorge cliffs revegetate or erode to a stable slope. The measurements demonstrate both the control exercised by sediment supply on transport rates and the persistent long-term impact of major floods on mountain streams. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: Colorado; dambreak; field study; flood impact; mountain stream; sediment supply; sediment transport

INTRODUCTION

Infrequent but high impact events are increasingly recognized to be important controls on channel evolution and sediment transport regime in upland areas. Catastrophic floods generated by rainstorms (e.g. McCain *et al.*, 1979; Schmidt, 1994), glacial lake outbursts (e.g. Hewitt, 1982; Vuichard and Zimmermann, 1987) and dam failures (e.g. Fearnsides and Wilcockson, 1928; Scott and Gravlee, 1968) carry more sediment in a matter of hours or days than has been transported in the previous decade or even century. They also leave an aftermath of altered sediment supply and channel morphology relative to the pre-flood conditions, which determines channel behaviour during the long periods of recovery which separate such events. An increased sediment availability can affect sediment yield for years after the flood (e.g. Newson, 1980). In addition, the naturally sensitive balance between sediment supply and transport at the upper end of the river system is altered, with repercussions potentially extending throughout the whole system (e.g. Schumm, 1977; Newson, 1981).

The long-term consequences of catastrophic floods are of interest to geomorphologists seeking to understand channel and landscape evolution. They are also relevant to engineers, who need to be aware that predictions of, for example, reservoir siltation rates, bridge stability and channel carrying capacity based on decades of observed channel stability before a major flood may need to be revised for post-flood conditions. However, there has been little research into the long-term recovery of sediment supply and transport in flood-affected mountain streams. Data are needed on the magnitude of raised sediment yields and on the period of time during which they may return to pre-flood levels. This paper therefore reports on the bedload transport regime of the Roaring River, Rocky Mountain National Park, Colorado, USA, which was ravaged by the flood from the Lawn Lake dam failure in July 1982. Data collected in 1995, 13 years after the flood, are compared with measurements made during 1984–88 to investigate the longer term variation of transport regime.

* Correspondence to: J. C. Bathurst, Water Resource Systems Research Laboratory, Department of Civil Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU, UK
† Current address: Centre of Excellence in Water Resources Engineering, University of Engineering and Technology, Lahore 54890, Pakistan

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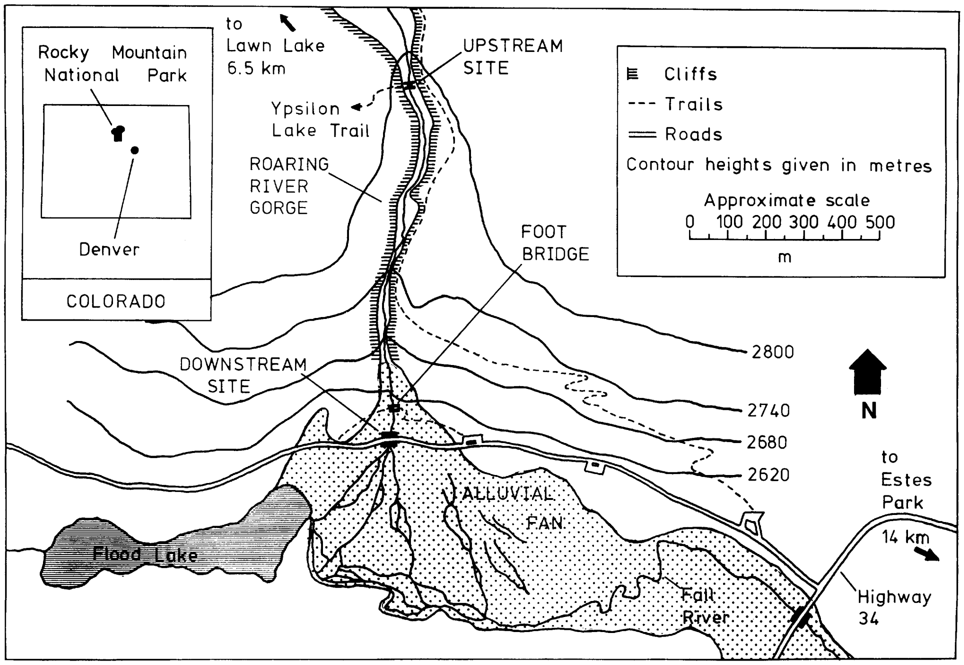

Figure 1. Sketch map of the Roaring River study area, Rocky Mountain National Park, Colorado, USA. The upstream site is the Ypsilon Lake Trail bridge; the downstream site is the Fall River Road bridge. Contour heights in metres are based on original data in feet

THE LAWN LAKE FLOOD

Peak flood discharges were estimated to be $500\,m^3\,s^{-1}$ at the Lawn Lake dam (elevation about 3350 m) and $340\,m^3\,s^{-1}$ 7·5 km downstream where the Roaring River joins the Fall River (elevation about 2620 m). These are far in excess of the normal snowmelt peak discharge of about $5\,m^3\,s^{-1}$ and the flood is likely to have been the largest in the valley since deglaciation 10 000 years ago (Jarrett and Costa, 1986).

Before the flood the Roaring River had a width of about 5–10 m, was bordered by grass and trees and had a generally stable boulder bed. Stream channels in the area are generally decoupled from sediment sources on the hillslope (e.g. Caine, 1984, 1986; Summer, 1990) with consequently low sediment transport other than as a function of occasional major events. Normal high flows are caused by snowmelt and summer thunderstorms.

Following the flood, the stream returned to its former width but was left in a 100 m wide swathe of unvegetated debris (grading from sand to boulders) and had a bed of fresh loose sediment. Just above the Fall River confluence the flood scoured a spectacular gorge in compacted glacial material and deposited a large fan of sand, gravel and boulders (Figure 1). The steep cliffs along the 0·75 km long gorge, up to 30 m high in places, were expected to form an important sediment source for the Roaring River and Fall River and the gorge was therefore the centre of a study into the relationship between sediment supply and transport. The upstream basin area at this point is about $29\,km^2$.

BEDLOAD TRANSPORT 1983–88

Studies of sediment transport in the Roaring River and Fall River in the years immediately after the dambreak flood (1983–88) are reported in Bathurst *et al.* (1986a,b, 1990), Pitlick and Thorne (1987) and Pitlick (1993). Other features are described by Jarrett and Costa (1986) and Blair (1987). An analysis of sediment fluxes in the Roaring River catchment is presented by Summer (1990).

The initial impact of the 1982 flood was a massive increase in the supply of loose material within and along the Roaring River channel. Sediment transport in 1983, a record snowmelt year, was correspondingly high but, with the resulting removal of much of this material and armouring of the bed, the impact was reduced in

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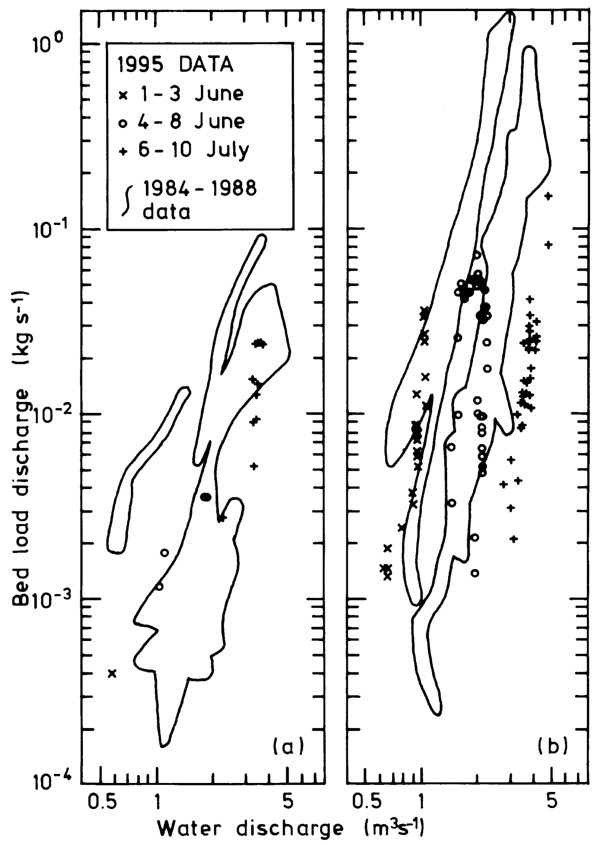

Figure 2. Variation of bedload discharge with water discharge at: (a) Ypsilon Lake Trail bridge (the upstream site); (b) Fall River Road bridge (the downstream site). Data of 1995 are compared with data bands of 1984–88

subsequent years. Nevertheless, it was estimated that bedload transport in the Roaring River was still an order of magnitude higher than would have been expected in the pre-flood channel (Bathurst *et al.*, 1990). By 1988 transport rates upstream from the gorge were perhaps declining but transport out of the gorge, maintained by supplies from cliff erosion, remained at enhanced levels. By contrast, in the Fall River below its confluence with the Roaring River, transport rates were considered to be returning to near pre-flood magnitudes by 1987 (Pitlick, 1990).

Two major sediment supply systems were identified at the seasonal scale (Bathurst *et al.*, 1986a). Initial snowmelt flows in May–June carried high bedloads, composed of material supplied to the channel by winter erosion processes. Rapid depletion of these supplies resulted in the bedloads of later flows being reduced by up to an order of magnitude for a given water discharge. The trend could be reversed in July and August, especially downstream from the gorge, when rainstorms dramatically increased cliff erosion and supplied new material directly into the channel. Plotting bedload discharge against water discharge yielded two data bands, one reflecting the high transport rates of early snowmelt and rainstorm flows, the other the lower transport rates of flows with depleted supplies (Bathurst *et al.*, 1990) (illustrated in Figure 2).

DATA COLLECTION IN 1995

Bedload measurements were made during 1–8 June and 6–10 July, representing periods of early and late snowmelt respectively. The main emphasis was on transport out of the gorge which was monitored, as in 1984–88, at the Fall River Road bridge on the alluvial fan (the downstream site). However, a few control data on transport above the gorge were also obtained, at the Ypsilon Lake Trail bridge (the upstream site) (Figure 1).

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Table 1. Channel parameters at the sampling sites

Period of validity	Channel width (m)	Channel slope ($m\,m^{-1}$)	Bed material size (mm)		
			D_{16}	D_{50}	D_{84}
Ypsilon Lake Trail bridge*					
8/6–18/7/84	6·25	0·0383	48	106	208
18/5–6/6/85	6·25	0·0360	52	104	211
7/6–12/6/85	6·25	0·0339	48	109	223
26/5–8/6/95	6·25	0·0323	33	93	229
5/7–11/7/95	6·88	0·0352‡	37	130	256
Fall River Road Bridge†					
8/6–25/7/84	10·9	0·0460	25	72	217
18/5–27/5/85	6·1	0·0523	32	77	156
27/5–6/6/85	6·1	0·0470	–	–	–
7/6–12/6/85	6·1	–	52	117	240
26/5–8/6/95	9·8	0·0481	35	84	151
5/7–11/7/95	7·5	0·0333‡	55	111	240

* Measurements made in a 30 m reach immediately upstream of the bridge
† Measurements made in a 25 m shoal reach about 50 m upstream of the Fall River Road bridge
‡ Approximate value

The measurement techniques are described in Bathurst *et al*. (1986b). Water discharge was obtained from stage measurements using a stage/discharge relationship derived from discharge gaugings with a Price AA cup current meter. Bedload transport was measured with a 150 mm aperture Helley–Smith sampler. On the assumption that the bedload moved in threads between the larger boulders, samples were collected at three points in each cross-section, representing the observed main flow streams. The total of each set of three samples was dried and weighed. The best estimate of bedload discharge was then obtained by multiplying this total by the ratio of transport thread cross-sectional area to sampled cross-sectional area (i.e. three times the sampler aperture cross-sectional area) and dividing by the total sampling time. The sampling time varied but was shorter (totals of 30–90 s) in June, when fine sediment caused clogging of the sampler mesh bag, compared with typically 180 s in July. For each total sample the maximum particle size was measured and in most cases the full size distribution was determined by sieving. Channel bed material size distribution at each site was obtained by Wolman's (1954) technique. Basic site data are given in Table I.

CONDITIONS IN 1995

A tendency towards cliff stabilization is evident at the upper end of the gorge, where the cliffs are lower and the floor is wider than in the central section. Since the dambreak flood, cliff erosion and deposition of material at the cliff base have resulted in a reduction in sideslope gradient, while vegetation is slowly establishing itself. In the central part of the gorge, though, cliffs remain steep and unvegetated. Runoff from rain and subsurface drainage has left the cliffs scoured by rilling. Debris accumulates at the cliff bases but much of this is removed by the stream.

May 1995 was one of the coldest and wettest Mays on record in the Colorado Front Range. A large snowpack remained in place, with little snowmelt, until mid-June. Stream discharges in early June were low (0·6–2 $m^3\,s^{-1}$). As a result of the moisture and other winter erosion processes, a large supply of material accumulated at the cliff bases, fed by local mudflows and collapses. Some of this material entered the stream where, as washload, it gave the water a continuously muddy colour.

In mid-June (in the absence of the field team) warm weather unleashed record snowmelt discharges. Slope-area calculations in July indicated the peak discharge to have been between 8 and 19 $m^3\,s^{-1}$ (probably nearer the lower rather than the higher figure), at least twice the previously measured snowmelt peak discharges. These flows flushed the loose sediment from the floor of the gorge (an effect shown by photographs from before and after the event) and caused major changes in channel morphology. The Roaring River channel had been stable since 1984. The mid-June flows must therefore have been the biggest since 1983 and probably since the dambreak flood itself.

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During early July, warm weather and a continuing snowpack kept discharges in the range 2–5 $m^3 s^{-1}$. Generally the water was clearer than in early June.

RESULTS

Bedload transport regime

Figure 2 compares the relationship between the bedload and water discharges with the data bands for 1984–88 for the two sites. The results are analysed in chronological order.

For 1–3 June the downstream site data fall on the high transport band for 1984–88. These data correspond to the early, albeit low, snowmelt discharges of 0·6–1·08 $m^3 s^{-1}$: the source of the sediment was probably material which had collected on the channel bed in the gorge during the winter. For 4–8 June, despite an increase in discharge to 1·1–2·2 $m^3 s^{-1}$, the data shift to the lower transport band. This suggests a depletion of the in-channel supplies and an inability (because the discharge is not high enough) to tap the major stores built up adjacent to the channel in the gorge. The close correspondence between the June 1995 data and the 1984–88 transport bands for the downstream site shows a continuing potential for bedload to be transported at rates comparable with those observed in the years immediately following the dambreak flood (although the peak transport rates are an order of magnitude lower than those of the earlier period). The results demonstrate also a continuing supply and exhaustion effect in bedload transport.

The pattern for early June is poorly defined at the upstream site but the few data lie along the low transport band. Transport rates for a given water discharge are generally lower, by up to an order of magnitude, than at the downstream site. This agrees with the conclusions of the 1984–88 study that the bedload transport into the gorge is unaffected by any upstream bank supply comparable with that in the gorge itself.

Although there are no measurements of transport during the mid-June snowmelt flows, it is clear from the removal of the gorge floor deposits and the changes in channel morphology that transport rates were high. Certainly transport out of the gorge must have exceeded pre-dambreak levels.

For 6–10 July the downstream data establish a new data band with transport rates an order of magnitude lower than those of the lower 1984–88 band. This indicates depletion of the gorge floor supplies by the mid-June flows. However, the high rate of increase of bedload discharge with water discharge observed in all the earlier studies (an exponent of four in a power relationship) is maintained and the larger transport rates may still exceed the pre-dambreak rates. At the upstream site the shift is less noticeable and the data remain in or close to the band containing the 1986–88 data (slightly lower than the 1984–85 band (Bathurst *et al*., 1990)). This suggests again a lower dependence of the transport regime on bank supplies at this site and a return to rates comparable with, or perhaps a little higher, than those of the pre-dambreak period.

Bed material size distribution

The variation in bed material size distribution (D_{16}, D_{50}, D_{84}, where D_n is the size of intermediate axis for which n per cent of material is finer) is shown for all the fieldwork periods in Figure 3. The most striking feature is the similarity of the 1985 and 1995 patterns at the downstream site. Both years began the snowmelt period with a very similar distribution. Both years then saw high snowmelt flows with extensive bedload movement, following which both exhibited again a very similar distribution, but coarser than at the start of the snowmelt period. Interpretation should be made with care because of the lack of information for the intervening years. However, the pattern is suggestive of a cycle in which there is build-up of finer material supplied from the gorge during the low flows of the winter period, followed by its removal and the creation of a coarser armour layer by the peak snowmelt flows. Such cycles are familiar from other studies (e.g. Wetzel, 1994). The repetition of the cycle in 1995 shows its potential for consistency and persistence, at least given the appropriate flow regime. The cycle is not evident at the upstream site. If anything, the D_{84} size there shows an overall coarsening with time, while the D_{16} size becomes finer. This indicates an absence of supply effects and a more purely hydraulic response to water discharge.

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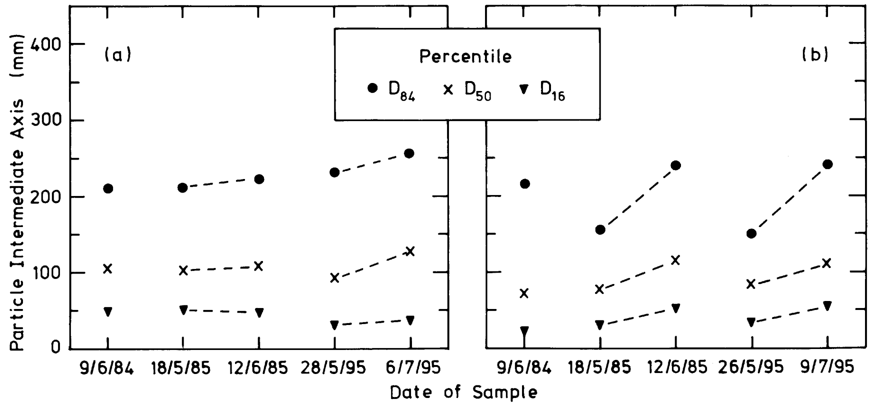

Figure 3. Variation of bed material size distribution at: (a) Ypsilon Lake Trail bridge; (b) Fall River Road bridge. Data of 1995 are compared with data of 1984 and 1985

CONCLUSIONS

This study provides quantitative evidence of the continuing impact of a catastrophic flood on bedload transport regime 13 years after the flood. It also illustrates the control which a single active sediment source can exert on channel transport.

(1) The continuing ability (as in June 1995) of bedload below the gorge to be transported according to the 1984–88 regime indicates that, as in the earlier period, bedload transport rates retain a potential to exceed their pre-dambreak values, at least for some of the time.
(2) The dominating control on bedload transport below the gorge is the supply of sediment from the gorge. Winter erosion processes provide the store of material which supports the continued enhanced transport rates, at least in the earlier snowmelt flows. Depending on the subsequent depletion of this material, later flows exhibit lower yielding transport regimes. The continuation of this annual cycle of supply and depletion, associated with the instability of the gorge cliffs, is further evidence of the long-term impact of the dambreak flood, since it was the flood which created the cliffs.
(3) Above the gorge, bedload transport is much less supply dependent and shows less evidence of cyclic effects. Transport rates are similar to the lower band rates of 1984–88, perhaps comparable with or a little higher than those of the pre-dambreak period. These characteristics agree with Pitlick's (1993) view of a return to stable conditions in the catchment (at least above the gorge).
(4) The impact of the peak snowmelt flows of mid-June 1995 shows that the channel created along the Roaring River following the dambreak flood is still adjusting to low frequency, high magnitude events. Such adjustments can release large amounts of sediment for transport.
(5) Bedload transport out of the gorge is likely to remain at enhanced levels until the gorge cliffs revegetate or stabilize at lower slope angles, processes which will take decades. However, the downstream impact of the raised transport rates is currently lessened since, following channel adjustments during the mid-June 1995 snowmelt flows, the Roaring River deposits its bedload in the Flood Lake rather than the Fall River (Figure 1).
(6) The evidence advanced above for the continuing impact of the dambreak flood is based on a limited dataset collected in only one field season. It shows that the enhanced bedload transport regime observed in the years immediately after the flood still had the potential to prevail 13 years on, at least for part of the time. However, because the 1995 study provides only a snapshot of the recovery process, the extent to which this potential remains characteristic of the long-term flood impact is not clear. Studies over several years are required to confirm the representative nature of the enhanced regime or of some other trend.

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REFERENCES

Bathurst, J. C., Leeks, G. J. L. and Newson, M. D. 1986a. 'Relationship between sediment supply and sediment transport for the Roaring River, Colorado, USA', in *Drainage Basin Sediment Delivery*, International Association of Hydrological Sciences Publication No. **159**, Institute of Hydrology, Wallingford, Oxon, UK, 105–117.

Bathurst. J. C., Leeks, G. J. L. and Newson, M. D. 1986b. 'Field measurements for hydraulic and geomorphological studes of sediment transport – The special problems of mountain streams', in Wessels, A. C. E. (Ed.), *Measuring Techniques in Hydraulic Research*, Balkema, Rotterdam, 137–151.

Bathurst, J. C., Hubbard, L., Leeks, G. J. L., Newson, M. D. and Thorne, C. R. 1990. 'Sediment yield in the aftermath of a dambreak flood in a mountain stream', in *Hydrology in Mountainous Regions, II*, International Association of Hydrological Sciences Publication No. **194**, Institute of Hydrology, Wallingford, Oxon, UK. 287–294.

Blair, T. C. 1987. 'Sedimentary processes, vertical stratification sequences and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park, Colorado', *Journal of Sedimentary Petrology*, **57**, 1–18.

Caine, N. 1984. 'Elevational contrasts in contemporary geomorphic activity in the Colorado Front Range', *Studia Geomorphologica Carpatho-Balcanica*, (Kraków), **18**, 5–31.

Caine, T. N. 1986. 'Sediment movement and storage on alpine slopes in the Colorado Rocky Mountains', in Abrahams, A. D. (Ed.), *Hillslope Processes*, Allen & Unwin, Boston, Massachusetts, 115–137.

Fearnsides, W. G. and Wilcockson, W. H. 1928. 'A topographical study of the flood-swept course of the Porth Llwyd above Dalgarrog', *Geographical Journal*, **72**(5), 401–419.

Hewitt, K. 1982. 'Natural dams and outburst floods of the Karakoram Himalaya', in *Hydrological Aspects of Alpine and High Mountain Areas*, International Association of Hydrological Sciences Publication No. **138**, Institute of Hydrology, Wallingford, Oxon, UK, 259–269.

Jarrett, R. D. and Costa, J. E. 1986. *Hydrology, geomorphology, and dam-break modeling of the July 15, 1982 Lawn Lake Dam and Cascade Lake Dam failures, Larimer County, Colorado*, US Geological Survey Professional Paper, **1369**, US Government Printing Office, Washington DC, 78 pp.

McCain, J. F., Hoxit, L. R., Maddox, R. A. Chappell, C. F., Caracena, F., Shroba, R. R., Schmidt, P. W., Crosby, E. J., Hansen, W. R. and Soule, J. M. 1979. *Storm and flood of July 31 – August 1, 1979, in the Big Thompson River and Cache la Poudre River basins, Larimer and Weld Counties, Colorado*, US Geological Survey Professional Paper, **1115**, US Government Printing Office, Washington DC, 152 pp.

Newson, M. D. 1980. 'The erosion of drainage ditches and its effect on bed-load yields in mid-Wales: reconnaissance case studies', *Earth Surface Processes*, **5**, 275–290.

Newson, M. D. 1981. 'Mountain streams', in Lewin, J. (Ed.), *British Rivers*, Allen & Unwin, London, 59–89.

Pitlick, J. 1993. 'Response and recovery of a subalpine stream following a catastrophic flood', *Geological Society of America Bulletin*, **105**, 657–670.

Pitlick, J. C. and Thorne, C. R. 1987. 'Sediment supply, movement and storage in an unstable gravel-bed river', in Thorne, C. R., Bathurst, J. C. and Hey, R. D. (Eds), *Sediment Transport in Gravel-bed Rivers*, Wiley, Chichester, 151–178.

Schmidt, K-H. 1994. 'River channel adjustment and sediment budget in response to a catastrophic flood event (Lainbach catchment, southern Bavaria)', in Ergenzinger, P. and Schmidt, K-H. (Eds), Dynamics and Geomorphology of Mountain Rivers, Springer-Verlag, Berlin, 109–127.

Schumm, S. A. 1977. *The Fluvial System*, Wiley, New York.

Scott, K. M. and Gravlee, G. C. 1968. *Flood surge on the Rubicon River, California – hydrology, hydraulics and boulder transport*, US Geological Survey Professional Paper, **422-M**, US Government Printing Office, Washington DC.

Summer, R. M. 1990. 'Development and application of a method to estimate short-term alpine sediment transfer in the Colorado Front Range, USA', *Mountain Research and Development*, **10**(4), 321–332.

Vuichard, D. and Zimmermann, M. 1987. 'The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences', *Mountain Research and Development*, **7**(2), 91–110.

Wetzel, K -F. 1994. 'The significance of fluvial erosion, channel storage and gravitational processes in sediment production in a small mountainous catchment area', in Ergenzinger, P. and Schmidt, K-H. (Eds), *Dynamics and Geomorphology of Mountain Rivers*, Springer-Verlag, Berlin, 141–160.

Wolman, M. G. 1954. 'A method of sampling coarse river-bed material', *Transactions of American Geophysical Union*, **35**(6), 951–956.

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